ASSESSMENT OF EROSION AND CORROSION BEHAVIOUR OF NICHROME COATED DUPLEX STAINLESS STEEL

A SYNOPSIS

Submitted by

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1. INTRODUCTION

Modern equipment must be designed under ever-stricter performance limits as technology, economy, and environmental concerns progress. Generally, this exceeds the tolerance limit of the component. This increased performance demand has the potential to significantly aggravate tribological defects like erosion and corrosion, which can lead to higher operational costs, reduced performance, and premature failure.

Pipelines are the arteries and veins of the oil and gas industries, since they are widely used in the oil and gas industries and perform a number of functions, such as transporting crude oil and natural gas from production fields to refineries, processing plants and distribution to consumers, it is obvious that these networks need constant monitoring and diagnosis. Some academic studies have examined the costly aspects of production losses, particularly those brought on by pipeline erosion corrosion problems, in an effort to prevent catastrophic failures that could have an adverse environmental impact. The demand for modern fluid handling systems to be more economical, dependable, and durable while guaranteeing fluid control is increasing. These cannot be achieved without minimizing the material damage caused by the two surface degradation mechanisms, erosion and corrosion. It has been extremely difficult to increase the performance of equipment in hostile environments since the open information is so inconsistent and deficient.

It is well accepted that developing an efficient erosion corrosion control is vital to gaining benefits such as greater plant availability, lower unscheduled maintenance, and reduced deferred costs. It is impossible to predict how quickly corrosion and erosion may cause a facility to degrade. This uncertainty can be minimised by conducting preventative and remedial studies for corrosion and erosive wear.

The implementation of an efficient erosion corrosion monitoring system will just reduce or eliminate the erosion corrosion-related degradation or damage to an asset. As a result of the development of numerous low cost and adaptive simulation test methodologies, laboratory research into the mechanisms of erosion-corrosion and examining the impact of operating variables on erosion corrosion rates are now considerably more realistic [1]. The significance of several parameters on erosion and corrosion has been established by a large number of fundamental experiments, nevertheless the behaviour of materials when pure erosion is followed by subsequent corrosion is not well understood, despite the fact that several studies have been

conducted to examine the erosion-corrosion behaviour of materials in complex environments. Although erosion-corrosion of steels was heavily studied in past decades. Most of these previous studies were focused on the general performances of the erosion enhanced corrosion and corrosion enhanced erosion It is reported that the impingements of the solid particles on the anodic sites could lead to pitting initiation at active states [2]. The impingements of the sand particles on a passive steel could induce the local breakdown of passive film, resulting in a sudden increase of the local anodic current. The synergy of erosion and corrosion could significantly influence the local chemical and electrochemical heterogeneity on the steel interface. Consequently, exploring the localized interaction between erosion and corrosion could facilitate understanding the degradation mechanism of carbon steel in liquidesolid particle mediums of various solution. Therefore, laboratory research is essential to reduce the probability of this exorbitant expense.

This shows how critical it is to study the behaviour of pipeline erosion and corrosion. In order to prevent erosion and corrosion damage, this study will examine the role thermal spray coating in improving mechanical characteristics and erosion and corrosion resistance. The earlier studies concentrated on the synergic effect of erosion corrosion [3], However, very few compared the effect of early erosion and eventual corrosion. The estimation of actual erosion–corrosion failure may not be accurate without considering these aspects. This triggers the research on the corrosion behavior of eroded specimens and optimization of erosion corrosion parameters through Taguchi based Grey Relational analysis.

2. LITERATURE REVIEW

Literature survey is carried out in order to know the basics and the importance of the proposed research and plan. Based on the thorough literature survey, the research gap and objectives are identified.

Oil & gas, petroleum, and other industries now depend upon pipelines as a reliable, essential item of equipment. The efficiency of the pipelines employed in the industrial process determines how efficiently it functions. Pipeline failure is a serious problem since it has a significant impact on both cost and production. Hu and Neville [4] reported that erosion corrosion is considered as most common types of damage in the oil and gas industry.

Solid particle erosion, a typical degradation of a material mode, is the loss of material that results from repeated impact of small solid particles or abrasive particles. Jindal et al. [5] explained that continuous impact of particles causes thinning due to the grooving of the solid particles on the surface, thereby, improvement in the erosion resistance of the material is the key factor to enhance the efficiency of the pipeline. Corrosion, the chemical/electrochemical interaction between materials and environments impacts the proper function of materials, which rapidly leads to their failure during service. Shi et al. [6] identified a need to understand more about erosion corrosion behaviour and to develop materials that are both extremely durable and functional.

Heitz [7] explained erosion-corrosion, a type of tribo-corrosion, damage metallic objects base and surface layers. Studies by Zhao et.al [8], Islam and Farhat [9], Shivalingaiah et al. [10] and Nguyen et al. [11] identified particle properties, impact angle, flow velocity and abrasive particles are the key determinants of mechanical erosion.

Material selection against erosion–corrosion necessitates involves material evaluation and design, as well as understanding the optimal selection. Francis and Byrne [12] studied the properties of duplex stainless steel (DSS) in erosion–corrosion resistance. Subbiah et al. [13] discovered that DSS contain almost equal percentage of austenite and ferrite phases which offer better mechanical qualities and high erosion–corrosion resistance. Renner et al. [14] identified the suitability of DSS 2205 in pipeline and oil gas industries which are subjected to erosion–corrosion.

Dhand et al. [15]concluded that thermal spray technique has been found to be the most efficient for creating a variety of coatings to improve the performance and longevity of engineering components subjected to various types of wear. Swain et al. [16] suggested thermal spray approach for deposition techniques offer protection against chemical, abrasive, erosive, and corrosive attacks is atmospheric plasma spray (APS) coating. Bolelli et al. [17] recommended DGun spraying over plasma spraying and other spraying processes due to its quick particle flight speed. Coatings with necessary adherence and characteristics can be obtained controlling the coating parameters.

Studies by Swaminathan et al. [18] has found that erosion corrosion resistance was improved when the substrate is coated with nichrome (NiCr) using appropriate coating

method. Studies showed that it can produce high hardness, minimal porosity, and good fracture toughness and protects base metal in terms of wear and corrosion resistance.

Khoddami et al. [19] successfully performed Solid particle erosion tests to investigate how different conditions influence the rate of erosion. Shahali et al. [20] performed the Electrochemical impedance spectroscopy and polarisation techniques to examine the specimen's corrosion behaviour under various conditions and estimated the rate. Repeated measurements are done to ensure that the aforesaid parameters are repeatable and reproducible. The optimization of erosion and corrosion is a multiobjective problem. Fu et al. [21] successfully optimized multiobjective problems by Taguchi-based grey relational analysis. Hence it was decided that the ideal method for optimizing this erosion corrosion is GRA method.

3. RESEARCH GAP

From the literature, the following research gap is identified:

- Duplex stainless steels (DSS) exhibit excellent corrosion resistance and mechanical properties to the severe environments, but study on erosion corrosion behaviour of DSS are limited.
- A great deal of information is available on coating using powders manufactured using traditional methods, but studies on powder made using the powder metallurgy technique are limited.
- The majority of the studies concentrated on the synergic effect of erosion corrosion, However, very few compared the effect of early erosion and eventual corrosion, estimation of actual erosion–corrosion failure may not be accurate without considering these aspects.
- Limited research has been conducted on duplex stainless steel coated with nichrome coating to identify the optimal thermal spray method among atmospheric plasma spray and detonation gun method in order to optimize the erosion and corrosion behaviour.
- The literature is not sufficiently comprehensive in exploring erosion and corrosion optimization. This concept acts as the basis for the suggested research project.

4. OBJECTIVES

Based on the research gap, the following objectives are formulated for the research work.

- Compare the substrate surface coating characteristics of APS and DGun coating techniques.
- Determine the impact of coatings on solid particle erosion.
- Investigate the corrosion behaviour by electrochemical polarization studies and electrochemical impedance spectroscopy analysis on the eroded specimens.
- Optimize the erosion corrosion behaviour using Grey Relational Analysis.

4.1 Proposed Methodology

The outline of the proposed research plan is as shown in Figure 1. The research work intends to find the, erosion corrosion behaviour with DGun and APS Coating / Without Coating on DSS2205 Alloy.

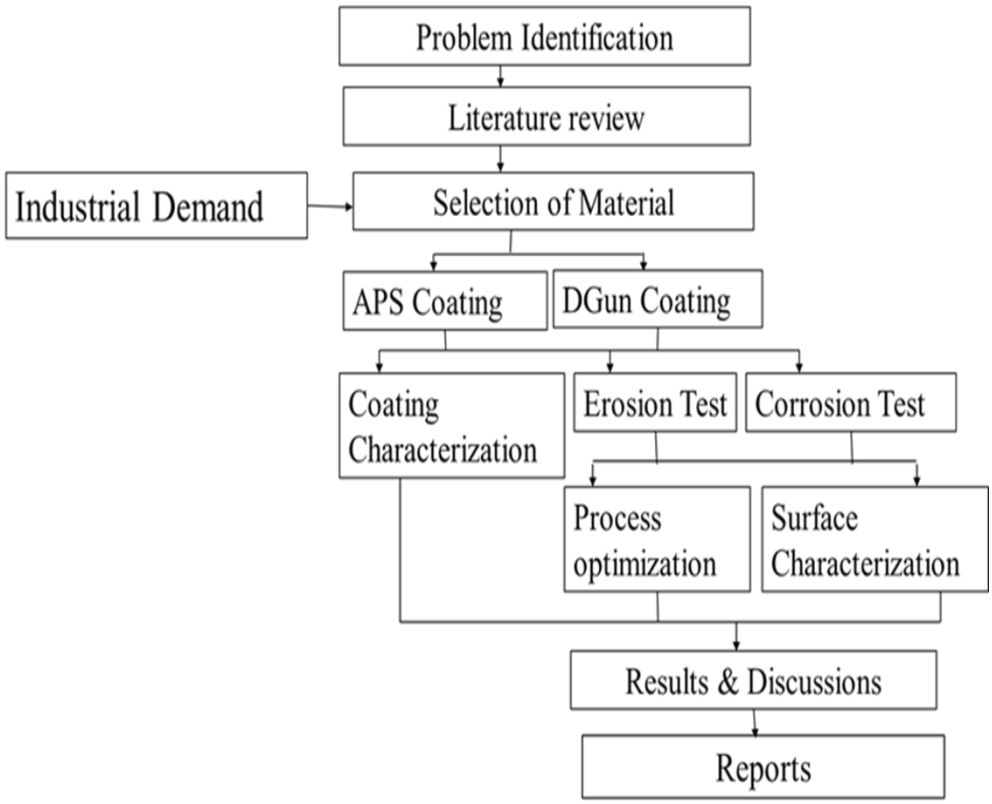


Figure 1: Research Framework.

4.2 Experimental Methodology

4.2.1 Coating

The substrate for coatings is the DSS2205, which has 25 x 25 x 5 mm dimensions. Nichrome (73.3% of nickel and 22.2% of chromium) with average particle size of 50µm is employed in this study. The APS coating has been carried out at Spraymet Surface Technologies Pvt. Ltd. Bangalore, India, DGun has been carried out at Sai Surface Coating Technologies Hyderabad, India. The process parameters are thoroughly optimized for a coating with a minimum thickness of 100µm.

4.2.2 Coating Testing

Metallographic methods were used to investigate the microstructural characteristics of the coated specimens. The porosity and surface characteristics of the coatings were examined.

4.2.4 Erosion Studies

The solid particle erosion tests were carried out as per the ASTM G76-02 standard at room temperature. The air jet erosion testing machine (TR-470, Ducom, Bangalore, India) was used to investigate the erosion with alumina oxide of size 50µm. The erosion test is performed at the particle velocity of 150,175,250m/s, flow rate 2.5,3.75,5g/min with impact angles of 30,60,90 degrees and time interval of 30 min. The samples were weighted before and after the erosion test with an electronic balance having accuracy of ± 0.01mg. By using the change in mass, erodent flow rate and discharge time, the erosion rate is calculated.

4.2.5 Electro-chemical Analysis

The electro-chemical corrosion was carried out in 3.5% NaCl solution. The potentiostat/ galvanostat (ACM instruments GillAC, UK) was used for the study... ASTM G3-14 standard was followed with corrosion cell exposed area of $1cm^2$, with the potential of – 250 mV to 250 mV at 1 mV/s as sweep rate to measure potential–current density. The values of Ecorr and Icorr are obtained by extrapolating Tafel plots. Then the exposed surface was subjected to metallurgical analysis using electron microscope and X-ray spectroscope.

5. RESULTS AND DISCUSSION

5.1 Microstructure Analysis

The coated and Uncoated specimens were subjected to microscopic analysis for determining the surface defects and structures.

5.2 Coating Characterization

The cross-sectional images of the DGun and APS coated samples show an average coating thickness of roughly 100μm and are free from cracks. Metallographic methods were used to investigate the microstructural characteristics of the coating

5.3 Erosion Behaviour

The erosion rate of coated and bare DSS 2205 alloy at different parameters is shown in Figure 2.

The erosion rate is maximum at the angle 30˚ and very low at the angle 90˚ for all specimens. The erosion rate is very low for DGun coated specimen for all the conditions. The erosion rate decreases with increasing impact angles. At impact angle 90˚ only vertical force acts on the surface and leads to less erosion rate when compared to other angles. For the angle 30˚ and 60˚ both forces are acting on the surface and the erosion rate is high at these impact angles. In impact angle 30˚ and 60˚ the surface area eroded in the form of cutting process and material sheared as chips. Therefore, the erosion rate is very high when compared to 90˚ impact angle.

Erosion rate is maximum at higher velocities (200m/s) and lower at Minimum Velocities (150m/s). When Flow velocity increases, the kinetic energy also increased gradually which produce more impact energy on the work piece material thereby removing more material from the surface. Gun coated specimens has the lowest erosion rate at all flow velocities.

The increase in discharge rate from 2,5 gm/min to 5gm/min has reduced the erosion rate for all the specimens. as Discharge rate increases, more amount of abrasives is produced which forms cluster and shielding the surface from further impact and hence it leads to lower material removal.

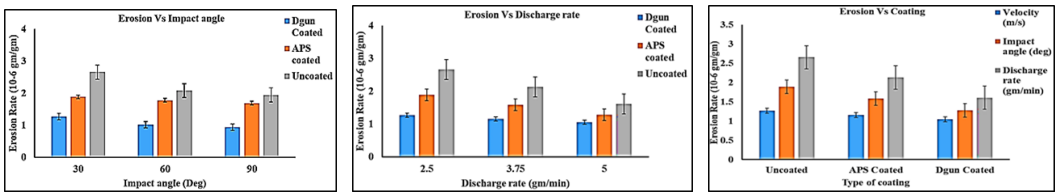


Figure 2: Effect of parameters on Erosion Rate

When the erosion characteristics of DGun coating, APS coating, and bare DSS 2205 are compared, it is clear that DGun nichrome coating has the lowest erosion rate. The effect of various parameters on erosion rate is shown in Figure 3

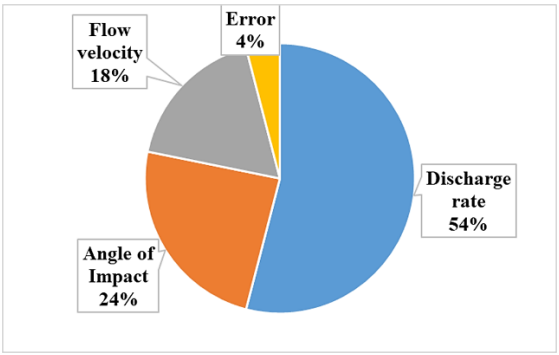
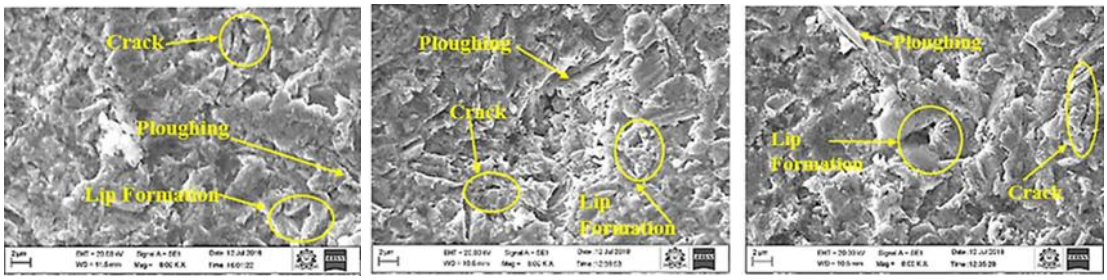


Figure 3: Effect of Parameters on erosion rate



(a) (b) (c)

Figure 4: a, b &c after erosion for DGun coated, APS coated and Uncoated specimens respectively

SEM analysis Figure 4 shows that erosion occurs in a mixed-mode regardless of the coating technique and they all have the same erosion mechanism. Wearing signs were seen on the surface at higher erosion rates. Craters, fractures, ploughings, and lip formations may cause the material to be removed. Furthermore, as the impact of the eroded particles increases, the cracks formed may contribute to the formation of craters and plowing marks. Furthermore, in these situations, the ploughing markings are deeper. These could be the reasons behind the material's higher rate of deterioration. The

appearance of smaller lip formations, ploughing, and wear markings on the eroded surface may be owing to the increased impingement angle, despite the low impact velocity. Micro cracks can also be found in the degraded area. The absence of deeper and darker craters, as well as lip fracture spots, could explain why specimens degraded less at low velocities and high impact angles.

5.4 Optimization of Erosion

The single objective optimization is carried out in order to identify the influence of each parameter on affecting Erosion. The optimum levels are found to be Coating DGun, Discharge rate 5gm/min, Flow velocity 150m/s, and Impact angle of 90^0. The ANOVA analysis revealed that coating contributed the most to the erosion rate (57%), followed by discharge rate (19%), impact angle (14%), and flow velocity (5%) as shown in Figure 5.

DGun coating had a higher density and lower porosity, the hardness values of DGun coatings are much higher than those of APS coatings and uncoated specimens. Increasing surface roughness intensifies erosive wear and mass loss significantly. The surface finish provided by DGun coating is far superior to APS coating and the uncoated specimen. This excellent surface finish will outperform all other specimens in erosion resistance. The residual stress on coating adherence to the substrate can influence the erosion rate. According to the literature, the plasma spray approach caused tensile residual stresses on coatings, whereas the DGun procedure induced compressive residual stresses on coatings. Increased erosion resistance is achieved by reducing residual stress and improving compressive strength. Resulting in improved erosion resistance. The increase in hardness will provide resistance to penetration, resulting in a slower rate of erosion. At optimum combination increases the erosion resistance by 73% and the error in prediction and experimental value is only 7.5 % hence the test results are validated.

A confirmation test was used to evaluate the proposed statistical approach, which revealed an error of less than 5% at a confidence level of 95%

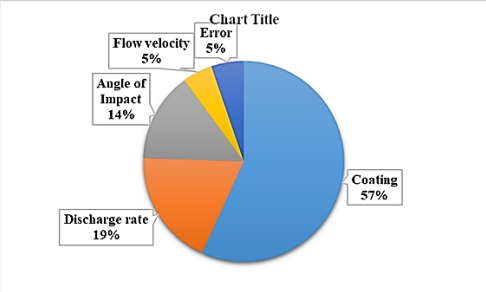


Figure 5: Effect of parameters on erosion rate

5.5 Electro-chemical Behaviour

The polarization curves are experimentally plotted for all the specimens in a solution of 3.5% NaCl at room temperature to determine the corrosion behaviour and the components of corrosion such as Ecorr, Icorr and corrosion rate (CR). Table 1 shows the experimental results for a sample specimen.

Table 1: Corrosion potential and density of DGun, APS coated and uncoated specimens

Coatings	Icorr (mV)	Ecorr (A/cm^2)	Corrosion rate (mmpy)
DGun	0.0010	-196.04	1.58
APS	0.0015	-259.12	1.89
Uncoated	0.0367	-263.25	2.86

Figure 6 displays the potentiodynamic polarization curves of NiCr coated by APS, DGun, and uncoated DSS2205. Ecorr results on APS coated NiCr indicates an increase in corrosion resistance of DSS2205. Compared to other specimens, Ecorr has dramatically dropped in the uncoated and coated specimens, showing that DSS2205 exhibits a clear inclination to corrosion. At the outset, DGun coatings have exhibited considerably lower rates of corrosion and deterioration than APS coatings. Even though uncoated DSS2205 is more corrosive, APS coating has provided a far higher level of corrosion resistance.

Various coating techniques result in different microstructures which in turn could result in a different corrosion resistance; hence the degradation rates and mechanisms are also different. The amount of porosity in the coatings that can expedite crack propagation

and coating removal. It is possible for electrolyte to penetrate into the coating/substrate interface and quicken corrosion.

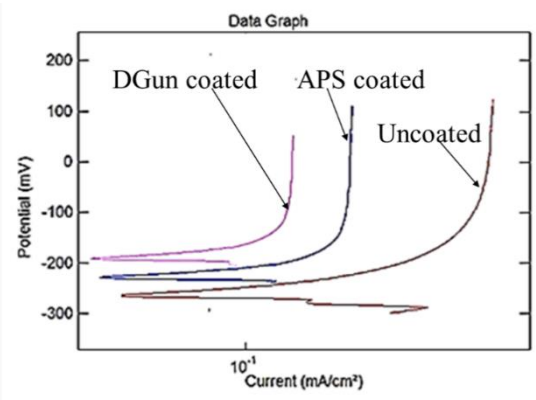


Figure 6: Potentiodynamic polarisation curves for coated and uncoated specimens during electrochemical corrosion

The structure and hardness of the coating are crucial aspects in the erosion-corrosion mechanisms. DGun coatings provide uniform and harder coatings on the surfaces when compared to that of APS coating and bare substrates. The increased presence of Cr can reduce the toughness of NiCr coatings and reduce the corrosion rates under corrosion. SEM analysis Figure 7 shows corrosion mechanism of the coating technique, and they all have the same mechanism.

(a) (b) (c)

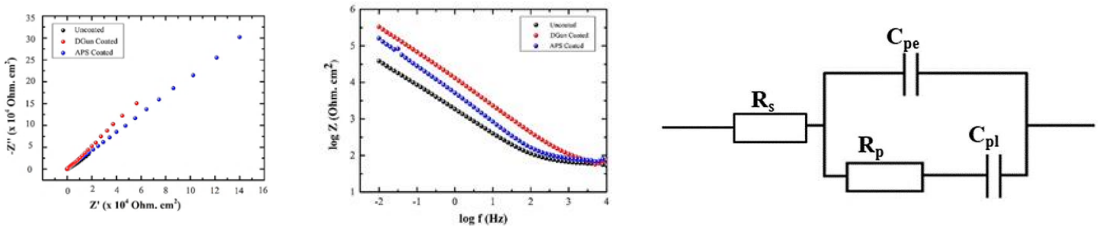
Figure 7: Surface morphology (a) DGun, (b) APS, (c) uncoated DSS2205 after electrochemical corrosion

The oxides and corrosion products such as chromium oxide produced on the coatings assist to the corrosion resistance of coated DSS2205. When the depth of cracks formed on the surfaces is compared, the DGun coated surface has only shallow cracks, whereas the uncoated specimen has extensive and deep cracks. Higher oxygen content indicates more corrosion. Chromium is more prevalent which indicates that an effective

protective layer is formed over the surface of the DGun coatings. The surface morphology of the uncoated DSS2205 shows the presence of micro flakes, granular scales, and spallation. According to the investigation, the scale has the most O2 and Fe. This shows the likelihood that Fe2O3 and Fe3O4 will develop the oxide scale. A few additional elements, like chromium (Cr) and aluminium (Al) are also present in the trace levels.

5.6 Electrochemical Impedance Spectroscopy (EIS) Analysis

EIS electrochemical testing was performed to understand the film formation and interphase inhibition at the electrode/electrolyte interface. After recording the EIS plots, the validity and robustness of the EIS data (Table 2) was evaluated. Nyquist diagrams, Bode plots and equivalent circuit are shown in Figure 8. The comparable electric circuit models that are used to analyse the impedance data. Rs, Rp, Cpe, and Cpl represent solution resistance, coating capacitance, coating resistance, and double layer capacitance respectively.



(a) (b) (c)

Figures 8: (a) Nyquist, (b) Bode plots (c) Equivalent circuit

Table 2: EIS spectra results

Sample	Rs (Ω cm^2)	Rp (Ω cm^2)	Cpe (μFcm^2)	Cpl (μFcm^2)
APS coated	54.95	21.9×10^3	315.8×10^{-6}	1.26×10^{-3}
Dgun coated	56.87	33.98×10^3	320.6×10^{-6}	1.09×10^{-3}
Uncoated	53.91	3.32×10^3	137.5×10^{-6}	11.53×10^{-3}

The Rp values of the DGun coating are always much higher than APS coated and uncoated surfaces. This shows that the DGun coating is more resistant to chloride ions which get through cracks.

5.5.2 Effect of various parameters on corrosion

The effect of various parameters on corrosion rate has been shown in Figure 9. An optimization was performed among the various coated and uncoated specimens and the optimum combination of parameters were identified. The results are shown in Figure 10

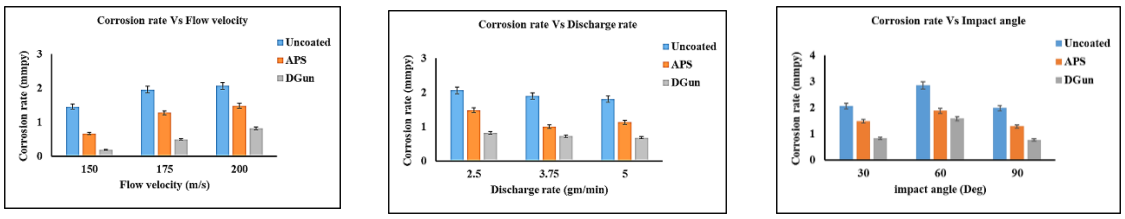


Figure 9: The effect of various parameters on corrosion rate

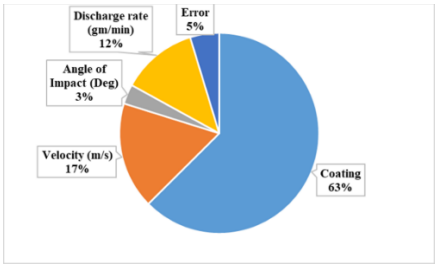


Figure 10: The effect of various parameters on the corrosion rate

5.6 Optimization of erosion corrosion

5.6.1 Grey relational analysis

The multi objective optimization is done by considering four input parameters namely coating, Flow velocity, impact angle and discharge rate with an aim to minimize erosion corrosion. The grade value and the rank for the data was calculated. The interrelation between the parameters were identified and the optimal combination for the combined erosion corrosion are DGun coating, Flow velocity = 150 m/s, Impact angle = 90^0, and Discharge rate = 5 gm/min. The major influencing factor on affecting the combined objective observed form the ANOVA analysis coating (58%), discharge rate (20%), flow velocity (12%) and impact angle (5%).The experiment was repeated with this combination and found that erosion resistance was increased by around 50% and corrosion resistance by 45%, an increase 44% also was obtained for grade. Figure 11 shows the effect of parameters on erosion corrosion The polarization curve for the optimal condition is shown in Figure 12.

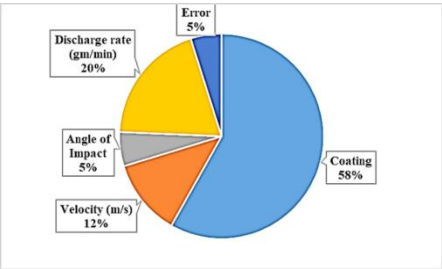


Figure 11: The effect of various parameters on the corrosion rate

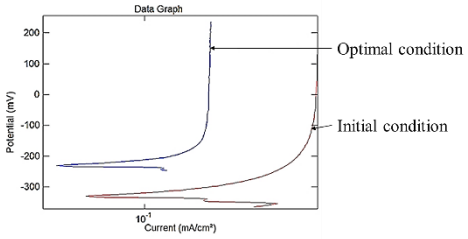


Figure 12: Polarization curve at optimal conditions

6. RESEARCH FINDINGS

- The DGun coating produces a better surface finish than the APS and uncoated specimens under the same conditions. The coating is sprayed more uniformly across the substrate surfaces as a result of the higher jet pressure, creating a better surface finish.
- As flow velocity increases, more material is removed by ploughing, leaving craters on the surfaces as the abrasive particles acquire more kinetic energy and break the bonding between the elements. and as a result, erosion is happening more quickly.
- The response table shows that the optimal parameters for achieving the best erosion resistance are flow velocity, discharge rate, impact angle, and coating. The resistance to erosion of the surface is improved by these input parameters.
- A larger tangential component of kinetic energy, which is created by lower impact angles, removes material through ploughing and cutting. Higher impact angles result in a decreased tangential component of kinetic energy, which causes plastic deformation and material removal. As a result, the erosion rate lowers as the impact angle increases.
- DGun coated DSS2205 has provided exceptional erosion corrosion resistance, due to its dense and consistent microstructure. The effectiveness of the coatings could be graded as follows from the best to the worst: DGun coated; APS coated; uncoated specimen.
- Compact microstructures and strong intersplat bonding in the DGun coatings contributed to a shorter transient oxidation stage. The constructive protective oxide scales have successfully blocked the entry of progressive corrosion.

- All coatings are sufficiently dense to stop chlorine ions reaching the coating substrate interface. In the presence of aqueous NaCl, the coatings possess the tendency to passivate.
- The EIS results indicate that the semicircle of the NiCr coated specimen by DGun method is greater than that of the uncoated and APS coated DSS 2205 specimens. This characteristic defines that the DGun coated NiCr sample has a higher polarization resistance than the uncoated and APS coated DSS2205 samples.
- The EIS findings indicate that it is possible to predict the rate of steel corrosion for NiCr coatings under operational conditions. The impedance characteristic of the corrosion system can be accurately described by the electrochemical impedance spectrum. This is due to its excellent accuracy while computing evaluation indices and evaluating data.
- The rate of corrosion of the coatings is evaluated by electrochemical impedance spectroscopy. The corrosion resistance of the NiCr coating by DGun was found to have increased by 70% when compared to a sample of bare stainless steel, but the APS coating only improved by 41%.
- The findings indicate that the optimum erosion corrosion parameters are DGun coating, Flow velocity = 150 m/s, Impact angle = 90^0, and Discharge rate = 5 gm/min. These input variables improve performance by lowering erosion corrosion wear.
- The ANOVA indicates that the most significant factors influencing erosion and corrosion are coating (58%), discharge rate (20%), flow velocity (12%). And impact angle (5%).

7. ORGANIZATION OF THESIS

- **Chapter 1: Introduction**: In this chapter, the coating materials and its classification, merits and the importance of thermal spray method over conventional methods are reported. The need and merits of different coating methods and the brief about the erosion -corrosion are discussed.

- **Chapter 2**: **Literature Survey**: This chapter deals about the detailed literature survey on the studies of Erosion -corrosion and grey relational analysis. The research gap is identified and the objective and the methodology proposed are also reported.

- **Chapter 3: Experimental Procedure:** In this chapter, methodology, proposed work, preparation of coating material, mechanical testing, experimental details of erosion corrosion are presented. In addition, the mechanical properties of the coated specimen are also reported.

- **Chapter 4: Results &Discussions**:

  4.1. Thermal spray coating: In this chapter, the effect of thermal spray coating on duplex stainless steel 2205 is compared with commercially available bare DSS 2205. The XRD analyse is carried out to find phases in the samples. Also, the effect of various coating techniques on hardness, surface finish and porosity were determined for DSS 2205 is reported in this chapter. The SEM analysis was performed to carry out to study the surface finish.

  4.2. Solid particle Erosion: This chapter deals with the erosion resistance coated and uncoated alloy. The erosion rate was determined by weight loss method and the surface morphology was discussed with the help of SEM images and EDAX analysis. Further, a single objective optimization is carried out and the optimal combination of parameters is determined which will improve the performance.

  4.3. Electrochemical corrosion: This chapter deals with the corrosion resistance coated and uncoated alloy in 3.5% NaCl solution. The corrosion rate was determined by TAFEL method and the surface morphology was discussed with the help of SEM images and EDAX analysis. Further, a single objective optimization is carried out and the optimal combination of parameters is determined which will improve the performance.

  4.4 Multiobjective Optimization: In this chapter, the multi objective optimization is carried out in order to identify the influence of process parameters content on the combined objectives. Further, erosion corrosion at optimized input condition and it is also examined through SEM. Taguchi based Grey Relation analysis technique is employed for monitoring the erosion corrosion performance on coated surfaces.

- **Chapter 5: Conclusions**: Based on the results and discussion, the conclusion of the research work and the scope for the future work is reported in this chapter. The conclusions are made for the research work and the future scopes of the work were discussed in this chapter.

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LIST OF PUBLICATIONS

1. **R. Kuruvila,** S.T Kumaran, U. Uthayakumar, M. A Khan, and F. Ahmed, Erosion behaviour of plasma and DGun sprayed nichrome coatings on 2205 duplex stainless steel, *International Journal on Interactive Design and Manufacturing* (2023), 1-15**.**
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1. **R. Kuruvila,** S.T. Kumaran, M. Uthayakumar, M.A. Khan, Electrochemical corrosion behaviour of thermally sprayed nichrome coating on duplex stainless steel, Journal of Testing and Evaluation.